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U.S. PATENT APPLICATION FOR
MICRO FLUIDIC SYSTEM FOR SINGLE MOLECULE IMAGING

by

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CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] --

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with United States government support awarded by the following agencies: DOE DE-FGO2-99ER62830 and NIH HG00225.

[0003] The United States has certain rights in this invention.

BACKGROUND OF THE INVENTION

[0004] The present invention relates to methods of manipulating molecules and, in particular, to a fluid transport system useful for straightening, aligning, and fixing long chain polymers such as DNA.

[0005] The analysis of nucleic acid molecules (e.g. DNA) and, in particular, the sequencing of such molecules may be aided by optical techniques in which long portions of such molecules are straightened and fixed to a substrate for microscopic analysis. The fixed molecule may be analyzed by creating "landmarks" on the molecule by attaching fluorescent markers to specific locations or by cutting it with restriction enzymes to form visible breaks at specific locations. The order and relative separation of the landmarks is preserved, because the molecule remains fixed, and may be used to produce an optical map of the molecule. The optical map provides a framework on which other sequence information may be assembled. The landmarks allow optical maps of fragments of long molecules to be assembled into the entire molecule by the process of matching fragments with similarly spaced landmarks.

[0006] The effective use of optical maps requires that large numbers of single molecules be processed. A number of techniques have been examined for the purpose of straightening and fixing large numbers of molecules including: (1) straightening the molecules in a flow of molten gel which is then hardened to fix the molecules in place and (2) straightening the molecules under capillary flow of a

carrier liquid or convective flow caused by evaporation of a carrier liquid and promoting adsorption of the elongated molecules to a substrate adjacent to the flow.

[0007] A different set of techniques has been investigated in which the molecules are straightened in a flowing carrier fluid without being fixed to a substrate. In these techniques, the molecules are analyzed as they move. While these latter techniques potentially provide the same benefits of preserving the order and relative separation of the landmarks, motion of the molecule complicates the process of imaging the molecule, makes some landmarking techniques difficult, and eliminates the possibility of preserving the molecule for later additional or more complex analysis.

[0008] Ideally, when molecules are fixed to a substrate, the fixed molecules should have sufficient separation so that molecules do not overlap or cross. Points of overlap create image artifacts that can severely hamper the analysis process.

[0009] It is typical to stain the fixed molecule with a fluorescent material which distributes itself evenly along the molecule allowing estimates of separation between landmarks (e.g., in numbers of base pairs) to be gauged by total fluorescence rather than strictly by length. Such fluorescence measurements work best if the elongation of the molecule during straightening is not so great as to decrease the fluorescence per length of the molecule to a background level. Inadequate elongation of the molecule, however, can make it difficult to identify the points cut by the restriction enzymes, which desirably separate slightly under relaxation of the elongated molecule to render the cuts visible.

[0010] Prior art techniques for elongating and fixing long chain molecules can produce excessive overlap among molecules and variation in molecule elongation.

SUMMARY OF THE INVENTION

[0011] The present invention provides a method for straightening and fixing polymeric molecules using well-controlled laminar flow in a micro-channel. The laminar flow within a micro-channel allows sufficient diffusion of the ends of the molecule so that they may attach themselves to the wall of the micro-channel to be adsorbed and fixed in their straightened configuration.

[0012] The present invention also provides an improved apparatus of fabricating micro-channels suitable for this technique using an elastic molding compound.

[0013] Additional embodiments of the present invention provide the ability to sort molecular fragments by length and simple mechanisms for producing the necessary controlled laminar flow.

[0014] Specifically, then, the present invention fixes and straightens polymeric molecules using a channel sized to provide laminar flow of a liquid along a channel length, the channel having at least a first wall providing electrostatic attraction to the polymeric molecule. A means is provided for passing the liquid and polymeric molecule through the channel to straighten the polymeric molecule by passage along the channel within the laminar flow and allow absorption of the polymeric molecule to the first wall of the channel in straightened form.

[0015] It is thus one object of the invention to provide an improved method of straightening and fixing polymeric molecules. The laminar flow may be controlled to provide more consistent elongation to the molecules and improved separation of the molecules with reduced overlap and better alignment.

[0016] The first wall of the channel may be transparent and, for example, constructed of glass.

[0017] It is thus another object of the invention to provide an optical mapping surface well suited for use with optical microscopes.

[0018] The first wall may be treated to have a positive surface charge of predetermined density.

[0019] Thus, it is another object of the invention to control the electrostatic attraction between the polymeric molecule and the optical mapping substrate for more precise control over the fixing process.

[0020] The first wall may be detachable from the channel.

[0021] It is another object of the invention to provide an optical mapping surface having improved accessibility and/or reusability.

[0022] The channel may have at least one end that provides a funnel section opening to a reservoir holding the liquid and polymeric molecules.

[0023] It is thus another object of the invention to provide a simple means for staging the polymeric molecules and one that allows introduction of the polymeric molecules into the channel with minimum breakage.

[0024] The means for passing the liquid and polymeric molecules through the channel may, for example, be a pressure pump attached to one end of the channel, for example, a syringe or other type of pump, or a negative pressure pump attached to the other end of the channel such as may draw the liquid through by pressure differential, also, for example, being a syringe or other type of pump. Alternatively, the means may be a reservoir acted on by a force resulting from centrifugal acceleration of the channel and reservoirs.

[0025] Thus, it is another object of the invention to provide a variety of means of producing the necessary controlled laminar flow in the channel.

[0026] The reservoir used when centrifugal acceleration provides the movement of the liquid may be an end well extending perpendicularly to the length of the channel and the apparatus may further include a housing allowing the end well and channel to be received by a centrifuge with the end well extending along a principal axis of centrifugal acceleration, and the channel extending substantially across the principal axis of centrifugal acceleration.

[0027] Thus, it is another object of the invention to provide a simple apparatus that makes use of a standard laboratory centrifuge to produce the necessary flows and which thus may be inexpensive and/or disposable.

[0028] The apparatus may include multiple end wells and multiple micro-channels.

[0029] Thus, it is another object of the invention to allow simultaneous parallel straightening and fixation of the same or different polymeric molecules to occur to increase the throughput of the analysis process.

[0030] The channel may include a region of varying cross-section to promote a gradient in the laminar flow rate.

[0031] Thus, it is another object of the invention to provide for a sorting of molecules by length, taking advantage of differences in diffusion rate of the ends of the molecule as a function of molecular length.

[0032] These particular objects and advantages may apply to only some embodiments falling within the claims and thus do not define the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0033] Fig. 1 is a perspective view of one embodiment of the present invention showing a micro-channel communicating between a staging reservoir, holding polymeric molecules in a carrier liquid, and a collecting reservoir, the micro-channel attached to the reservoirs by funnel portions reducing shear and promoting laminar flow in the micro-channel and showing the use of a syringe pump to draw liquid through the micro-channel;

[0034] Fig. 2 is a cross-sectional view of the channel along lines 2--2 of Fig. 1 showing the increasing velocity of the laminar flow in the micro-channel toward the center of the micro-channel and an elongated DNA molecule centered in the micro-channel by the laminar flow;

[0035] Fig. 3 is a fragmentary view similar to Fig. 2 showing: a diffusion radius of one end of a polymeric molecule prior to adsorption to a wall of the micro-channel; a polymeric molecule having a trailing end attached to the wall of the micro-channel; and a polymeric molecule having a leading end attached to the wall of the micro-channel prior to adsorption of the entire length of the polymeric molecule to the wall of the micro-channel;

[0036] Fig. 4 is a cross-sectional view of multiple micro-channels during a first step of manufacturing the micro-channels in which a mold is used with an elastic molding compound to form upper walls of the micro-channels;

[0037] Fig. 5 is a figure similar to Fig. 4 showing removal of the mold and attachment of the upper walls of the micro-channel to a glass optical mapping surface in a second step of manufacturing;

[0038] Fig. 6 is an elevational, cross-sectional view of an alternative embodiment of the present invention in which centrifugal acceleration acting on a fluid head in the staging reservoir causes laminar flow in the micro-channel;

[0039] Fig. 7 is a plan view of the embodiment of Fig. 6 showing multiple parallel micro-channels each with staging wells and receiving wells;

[0040] Fig. 8 is a perspective view of the embodiments of Figs. 6 and 7 as placed in a standard centrifuge cup, the latter in partial cut-away;

[0041] Fig. 9 is a simplified diagram of rotation of centrifuge cup of Fig. 8 showing the vectors of motion and centripetal acceleration;

[0042] Fig. 10 is a plan view of an alternative micro-channel design providing varying cross-sections and inversely varying flow velocity such as may be used to sort polymeric molecules by size along the length of the micro-channel; and

[0043] Fig. 11 is a flow diagram of the process of using the present invention to straighten and fix polymeric molecules.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0044] Referring now to Fig. 1, the apparatus 10 of the present invention provides a generally planar channel plate 12 into which a longitudinally extending micro-channel 14 is formed, flanked by a staging reservoir 16 and a collecting reservoir 18 positioned at longitudinal ends of the channel plate 12.

[0045] Junctions between the longitudinal ends of the micro-channel 14 and staging reservoir 16 and collecting reservoir 18 are tapered to create funnel sections with narrow ends attached to the micro-channel 14 and wide ends attached to one of the staging reservoir 16 or collecting reservoir 18. The funnel sections 20 provide a smooth transition of fluid from the staging reservoir 16 through the micro-channel 14 to the collecting reservoir 18 thereby promoting laminar flow within the micro-channel 14 and reducing breakage of polymeric molecules as will be described.

[0046] One common wall of the staging reservoir 16, the collecting reservoir 18, and the micro-channel 14 is provided by an optical mapping substrate 22 attached to the channel plate 12. The substrate 22 thus encloses the staging reservoir 16, the collecting reservoir 18, and the micro-channel 14. The substrate 22, for example, may be a glass slide, treated as will be described below

[0047] In the embodiment of Fig. 1, a sample introduction port 24 may be formed in the optical mapping substrate 22 at the staging reservoir 16 to allow the introduction of polymeric molecules 36 and a carrier liquid 26 to the staging reservoir. In particular embodiments, the sample introduction port 24 may be used for pressure equalization when materials are drawn through the micro-channel 14 or for the attachment of a pump to pressurize the staging reservoir 16 to cause materials to flow through the micro-channel 14.

[0048] Similarly, a sample extraction port 27 may be formed in the optical mapping substrate 22 at the collecting reservoir 18 for removal of material, pressure equalization, or as shown, the attachment of pump 28 to draw the materials through the micro-channel 14. Alternatively, the ports 24 and 27 may be formed in the channel plate 12

[0049] In the embodiment of Fig. 1, the pump 28 is a syringe pump providing precisely metered flow using an electromechanical actuator and control system as is well understood in the art. The syringe pump draws carrier liquid 26 and polymeric molecules 36 from staging reservoir 16 through the micro-channel 14 in the collecting reservoir 18 at a controlled flow rate as may be set to provide the desired laminar flow within the micro-channel 14.

[0050] Specifically, referring to Fig. 2, the laminar flow 30 of carrier liquid 26 and polymeric molecules 36 within the micro-channel is such as to provide flow 32 parallel to the longitudinal walls of the micro-channel 14 with greatest flow velocities toward the cross-sectional center of the micro-channel 14 thereby defining a flow velocity profile 34. The flow rate of the pump 28 and the size of the micro-channel 14 is selected to provide flow velocity profile 34 that promotes straightening of the particular polymeric molecule 36 contained within the carrier liquid 26 with the polymeric molecule 36 roughly centered within the lumen of the micro-channel 14. These setting may be determined empirically by visual observation of the polymeric molecules 36 at different flow rates. Generally, laminar flow may be distinguished from capillary flow in which the liquid is drawn along the surface of the micro-channel 14 walls by a hydrophilicity of those walls and where the center leading flow velocity profile 34 is not obtained.

[0051] In a 50-micrometer wide micro-channel 14, for example, the velocity of flow 32 may range from 15 to 70 micrometers per second as measured across the lumen of the micro-channel 14.

[0052] In one embodiment, the cross-sectional width 38 of the micro-channel 14 is 50 micrometers and is preferably less than 100 micrometers. More generally, it is believed that the width 38 will be between one and one hundred times the straightened length 40 of the polymeric molecule 36.

[0053] Referring now to Fig. 3, although the inventors do not wish to be bound by a particular theory, it is believed that the ends 42 of the polymeric molecule 36 are more mobile than the remainder of the polymeric molecule 36 and may be modeled as having an effective diffusion radius 44 during the time the polymeric molecule 36 is in transit in the micro-channel 14 and generally greater than the polymeric molecule 36 as a whole. The average flow rate of the carrier liquid 26 for the flow velocity profile 34 and the width 38 of the micro-channel 14 is thus adjusted so that this effective diffusion radius 44 is equal to or greater than the width 38 of the micro-channel 14. In this way, at some time during transit of the polymeric molecule 36 within the micro-channel 14, contact by one end 42 of a large number of the polymeric molecules 36 with the substrate 22 can be expected. This contact will cause an electrostatic bond between the substrate 22 and the end 42 of a polymeric molecule 36.

[0054] Either the leading or the trailing ends 42 of the polymeric molecule 36 may be the first to attach to the substrate 22. As indicated by polymeric molecule 36', if the trailing end 42' of the polymeric molecule 36" is the first to contact the substrate 22 it is believed that continued flow of the carrier liquid 26 pulls the remainder of the polymeric molecule 36 against the substrate 22 to be held there by electrostatic attraction in a straightened state. Conversely, as indicated by polymeric molecule 36", if the leading end 42" of the polymeric molecule 36" is the first to contact the substrate 22 it is believed that continued flow of the carrier liquid 26 rolls the remainder of the polymeric molecule 36 over and then draws it against the substrate 22 to be held there by electrostatic attraction in a straightened state.

[0055] In order to promote and control attachment of the polymeric molecule to the substrate 22, the substrate 22 may be treated to establish a positive charge density on its surface contacting the carrier liquid 26. For example, the surface may be derivative with silage compounds, for example, those discussed in U.S. Patent 5,720,928 hereby incorporated in its entirety by reference.

[0056] Whereas the micro-channels 14 and optionally the staging reservoir 16 and collecting reservoir 18 of the apparatus 10 may be constructed in silicon using conventional photolithographic techniques, in a preferred embodiment of the present

invention, the micro-channels 14 (and optionally the staging reservoir 16 and collecting reservoir 18) are constructed using a molded elastomeric polymer.

[0057] Referring now to Fig. 4, in particular, a mold 45 providing a planar substrate 46 with upstanding ridges 48 defining the volume of the micro-channels 14 may be fabricated using conventional photolithography in which a light sensitive photoresist is applied to a silicon wafer that will form the mold 45. The photoresist is hardened by selective optical exposure and the unhardened portions washed away so that the photoresist provides a mask in the regions of the upstanding ridges 48 (e.g., the regions of the micro-channels 14 and the staging reservoir 16 and collecting reservoir 18). The silicon wafer is then etched to a depth of 7 to 8 micrometers defining the height of the micro-channel 14.

[0058] Referring still to Fig. 4, an elastomeric polymer, preferably poly(dimethylsiloxane) "PDMS") is then poured over this mold 45 to create the channel plate 12. The PDMS channel plate 12 is then peeled from the mold 45 and exposed to oxygen plasma to make it hydrophilic.

[0059] As shown in Fig. 5, the channel plate 12 may then be adhered to the substrate 22 creating the micro-channels 14 and optionally the staging reservoir 16 and collecting reservoir 18. The PDMS of the channel plate 12 will naturally adhere to glass in a releasable manner to produce a leak resistant seal. The seal is strong enough to resist leakage of fluids filling the micro-channels for the pressures used in this process yet weak enough to be reversible, and thus make the channel plate 12 and substrates 22 reusable.

[0060] By treatment of the substrate 22, as described above, to impress upon it a positive charge, and lack of treatment of channel plate 12 or by a treatment that promotes a negative surface charge on the channel plate 12 (?) preferential adsorption of the polymeric molecules 36 by the substrate 22 may be promoted. Optical mapping of the fixed polymeric molecules 36 may then be done through the transparent glass substrate 22 by means of an inverted microscope objective 50 such as a Zeiss Axiovert 135M such as is readily commercially available. Before the optical mapping, the polymeric molecule may be treated with fluorescent markers or restriction enzymes as are understood in the art.

[0061] Alternatively, because the channel plate 12 is attached to the substrate 22 releasable, the substrate 22 may be removed from the channel plate 12 and the top surface of the substrate 22 may be imaged. The removal of the channel plate 12 may also assist in further treatment of the fixed polymeric molecules 36, for example, with restriction enzymes and the like and the drying of these molecules to further promote adhesion. The ability to separate the channel plate 12 and substrate 22 allows one or both of these elements to be reused if desired.

[0062] Referring now to Fig. 6, in an alternative embodiment to that shown in Fig. 1, the height of the staging reservoir 16 and a collecting reservoir 18 may be increased and ports 24 and 27 provided through the channel plate 12 opposite the substrate 22. Upon initially filling staging reservoir 16 with carrier liquid 26 and polymeric molecules 36, a pressure head 52 is created being the difference in liquid height in staging reservoir 16 and a collecting reservoir 18. The small size of the micro-channel 14 limits flow from the staging reservoir 16 to the collecting reservoir 18 under normal gravitational acceleration after limited capillary flow.

[0063] Referring now to Fig. 8, the substrate 22 of the embodiment of Fig. 6 may be attached to a weighted carrier 54 that fits within the cup 56 of a standard swing bucket centrifuge 58 with the channel plate 12 supported to be level with the top of the cup 56 and the staging reservoir 16 and collecting reservoir 18 extending upward therefrom. The weighted carrier 54 is constructed so that the combination of the channel plate 12, the substrate 22, and the weighted carrier 54, when in position in the cup 56, have a center of mass 57 below the pivot 55 about which the cup is free to rotate.

[0064] When the centrifuge is started, as shown in Fig. 9, rotation 60 of the cups 56 swings them outward under the influence of a radial centripetal acceleration 62 acting on the center of mass 57. The acceleration promotes a downward force 64 shown in Fig. 6 on the carrier liquid 26 sufficient to cause the desired laminar flow through the micro-channel 14. By sizing the aperture of the micro-channel 14, and controlling the initial pressure head 52, the desired flow rate may be achieved.

[0065] Referring to Figs. 6 and 7, a single channel plate 12 may incorporate multiple staging reservoirs 16, collecting reservoirs 18 and intervening micro-channels 14.

As the pressure head 52 drops with flow through the micro-channel 14, the flow rate through the micro-channel 14 will also decrease. Control of this rate of decrease can be obtained by adjusting the relative diameter or cross-sectional area of staging reservoir 16 compared to collecting reservoir 18. For example, by making the collecting reservoirs 18 of bigger diameter than the staging reservoirs 16, the pressure head 52 decreases more slowly. By making the diameter of the reservoirs 16 and 18 large with respect to the flow rate or concentrating the polymeric molecules in the bottom of the staging reservoir 16, the molecules will pass through the micro-channel 14 only during the initial flow period providing more constant flow and transit time of the polymeric molecules 36 through the micro-channel 14.

[0066] Referring now to Fig. 10, in an alternative embodiment, the micro-channel 14 may be given a varying cross-sectional area so that for a given net flow rate 65 a series of different flow velocities V_1 through V_3 will be created at different locations along the micro-channel 14. It is believed that these varying flow velocities may effect a spatial separation of polymeric molecules 36 according to their length. This length sorting may be desirable to separate shorter polymeric molecules 36 from overlapping with longer polymeric molecules or for analytic separation of polymeric molecules 36 by length such as currently is done with electrophoresis.

[0067] Referring now to Fig. 11, the present invention may be incorporated as part of an optical mapping system. At a first step 70 of such a system, a solution, typically of water and polymeric molecules, for example, DNA, is prepared by techniques well known in the art. The polymeric molecules 36 may be treated with a condensing agent such as spermine causing them to coil, thereby reducing their damage during transfer to the apparatus 10 described above.

[0068] At step 72, the water (which will act as the carrier liquid 26) and polymeric molecules 36 are inserted into the staging reservoir 16. In the staging reservoir 16 they may be treated, for example, with a saline solution to decondense the molecules over a period, loosening their spermine-induced coiling. Once decondensed, the carrier fluid 26 and polymeric molecules 36 flow through the micro-channel 14

driven by a pump, centrifuge, or other method. During the flow, polymeric molecules 36 attach to the substrate 22 in straightened configuration.

[0069] Additional treatment of the fixed polymeric molecules 36 may be performed, as indicated by process block 74, by a variety of methods known in the art including but not limited to tagging with fluorescent materials or cutting by restriction enzymes. This step may include staining the polymeric molecules 36 with a fluorescent dye to provide accurate measurement of segments of the polymeric molecules 36.

[0070] These treatments may be performed either by passing additional liquids through the micro-channels 14 or by peeling back the channel plate 12 to allow direct access to the polymeric molecules 36 fixed to the substrate 22.

[0071] At process block 76, optical mapping of the fixed and treated polymeric molecules 36 may be performed either through the transparent optical mapping substrate 22 or by removing channel plate 12. After optical mapping, the fixed polymeric molecules 36 may be stored.

[0072] The laminar fluid flow used in the present invention, in contrast to radial or other capillary fluid flows is believed to reduce the number of overlapping molecules. The controlled laminar flow may also provide more consistent elongation or stretching of the polymeric molecules 36.

[0073] It is specifically intended that the present invention not be limited to the embodiments and illustrations contained herein, but include modified forms of those embodiments including portions of the embodiments and combinations of elements of different embodiments as come within the scope of the following claims.